Studies of TMDs at JLab 12 GeV

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INFN-Rome and Italian National Institute of Health

Structure of Nucleons and Nuclei 2013

10-14/June/2013 – Palace Hotel, Como

Outline

- JLab at 12 GeV
- Experimental equipment
- TMDs related experiments
- (some) expected results
- Conclusions

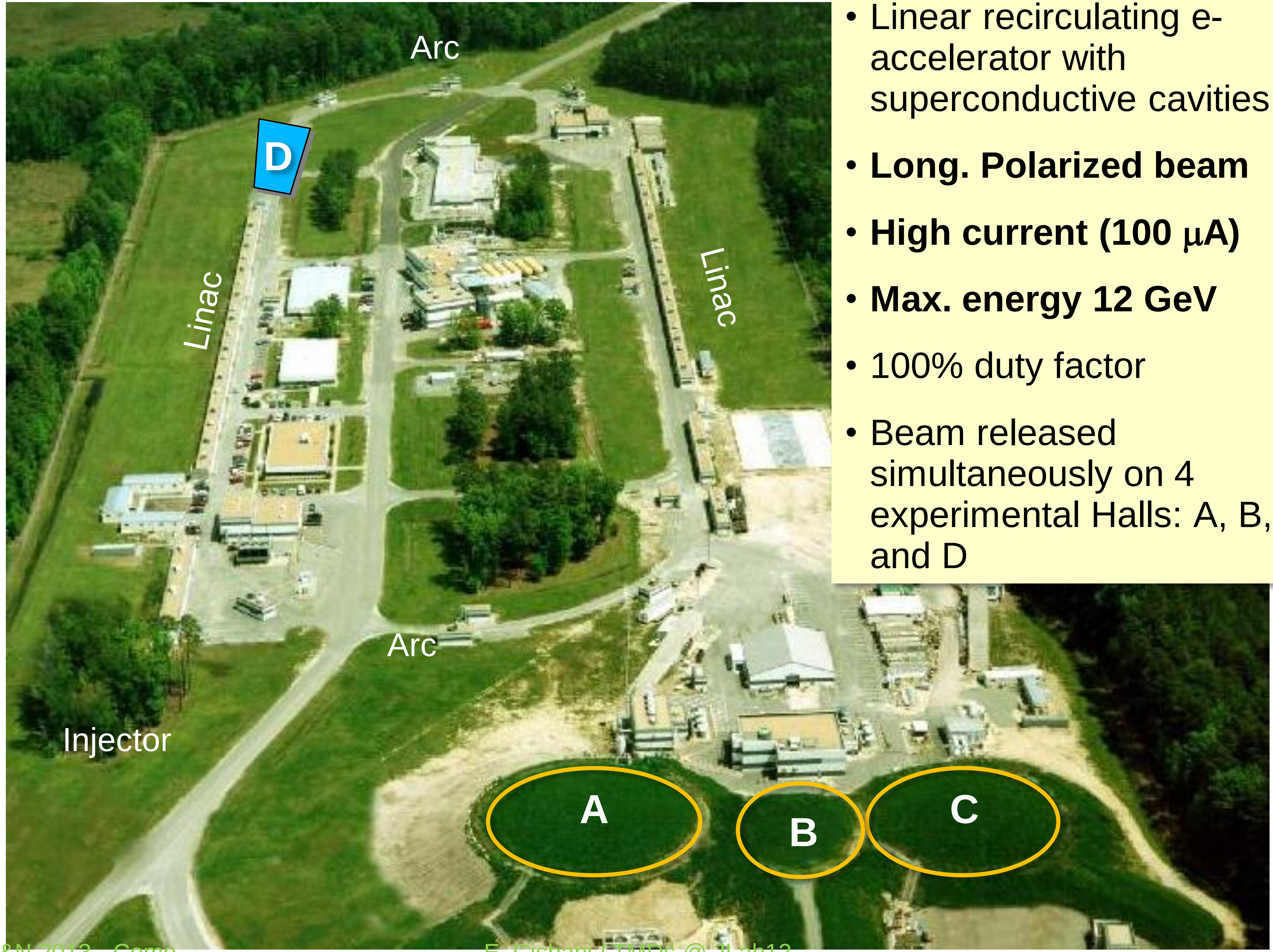
Contributions from:

H. Avakian, P. Rossi,

SIDIS JLab group,

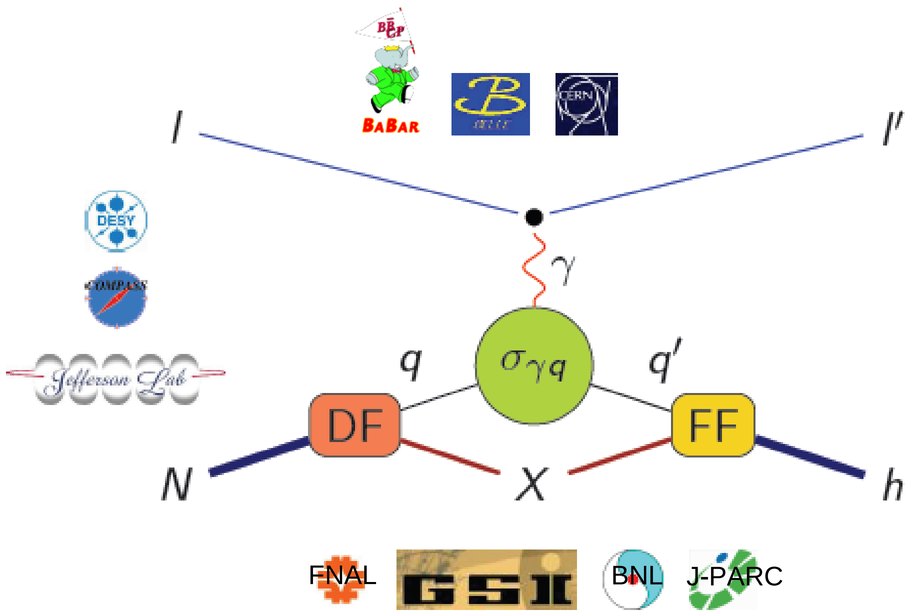
JLab/SIDIS experiments authors

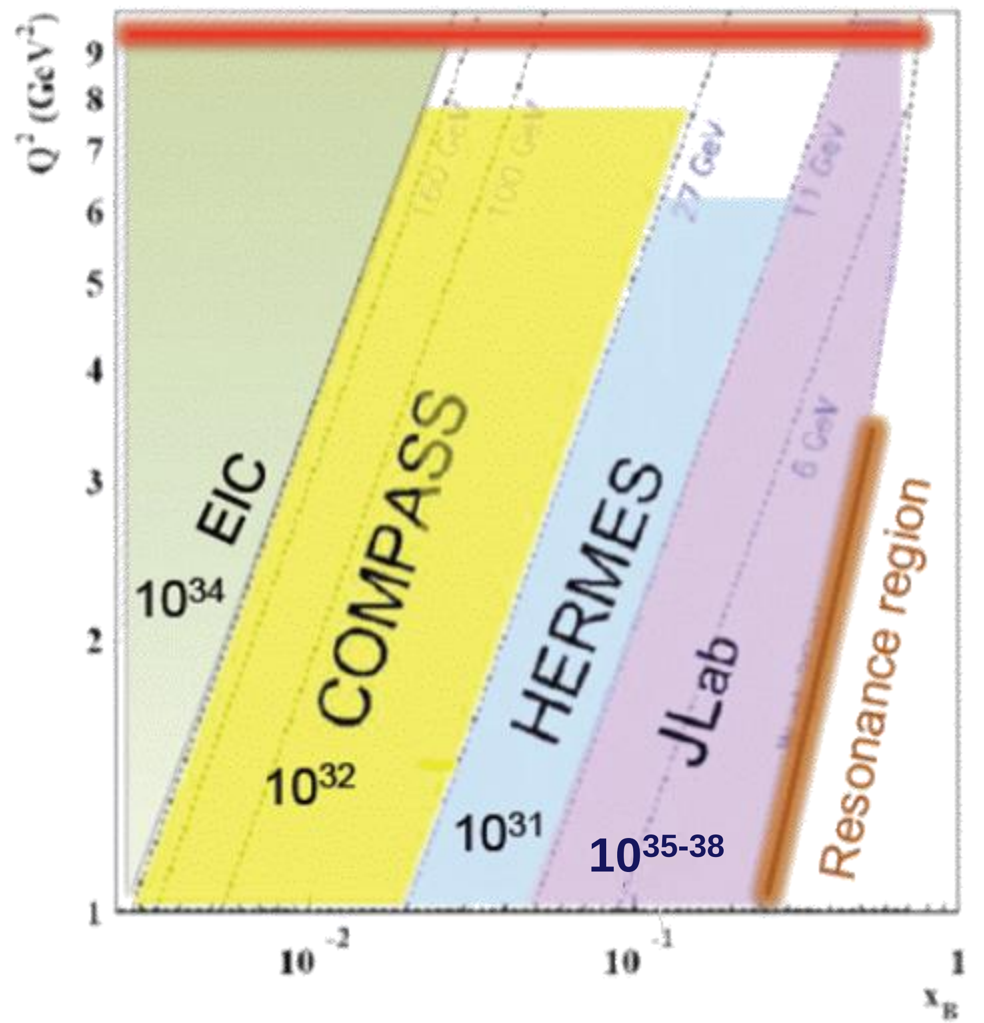
CEBAF in 2014



- Linear recirculating e- accelerator with superconductive cavities
- **Long. Polarized beam**
- **High current (100 μA)**
- **Max. energy 12 GeV**
- 100% duty factor
- Beam released simultaneously on 4 experimental Halls: A, B, C and D

(SI)DIS: TMD and FF





Access nucleon structure by SIDIS

$$\sigma^{lN\to lhX} \sim \sum_q e_q^2 \int d^2\vec{k}_T\, d^2\vec{p}_T\, d^2\vec{l}_T\; f^{N\to q}(x,k_T;Q)\cdot\sigma_{\gamma q}(y,k_T;Q)\cdot D^{q\to h}(z,p_T;Q)\;\delta(z\vec{k}_T+\vec{p}_T+\vec{l}_T-\vec{P}_T)$$

factorization and universality ... but it is still a complicated business

(some) Experimental directions

Improve statistics

- Simultaneous extraction of different moments
- Disentangle dependencies on relevant variables
- Reduce statistical errors

Access unexplored phase space

- Toward high x / Valence region
- P_T dependence
- Q^2 dependence

Measure poorly known TMDs / extract different flavours

- Measure moments by:
  - Different beam/target spin states
  - Different final state hadron(s) (π,K)
- Access Higher twists

Experimental Challenges

Beam:
"high" energy, intensity, stable, polarized

Targets:
high performance, different types, polarized

Detectors:
large acceptances, support high background, hadron identification

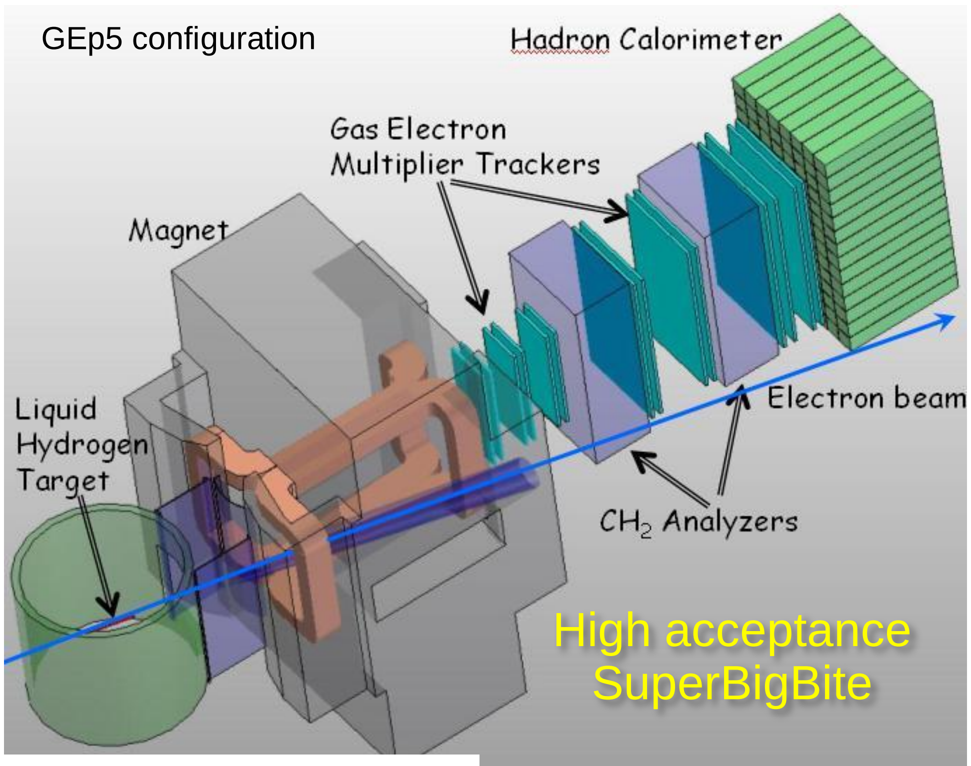
... and keep systematics under control !

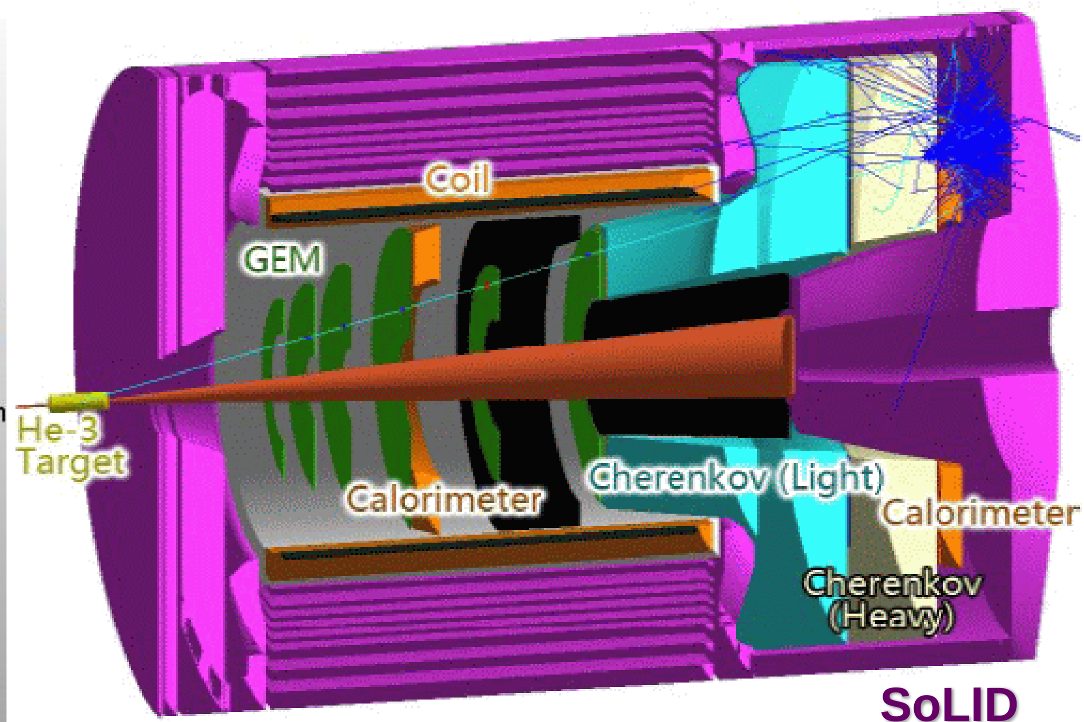
JLab Hall A

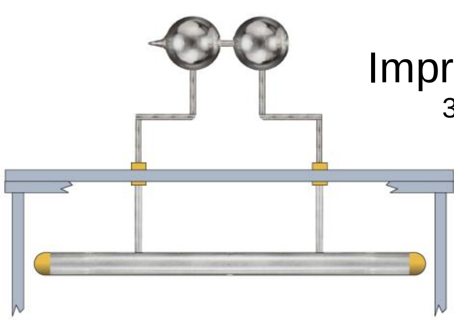
Detectors with moderate to large acceptance: BigBite (existing), SuperBigBite (2015),

SoLID/solenoid spectrometer (>2017)

High luminosity: few 10^{38} cm^{-2} s^{-1} New (polarized) targets







Improved unique
^{3}He polarized
Ttarget

Precision measurement on neutron/^{3}He and proton

Forward region, high x

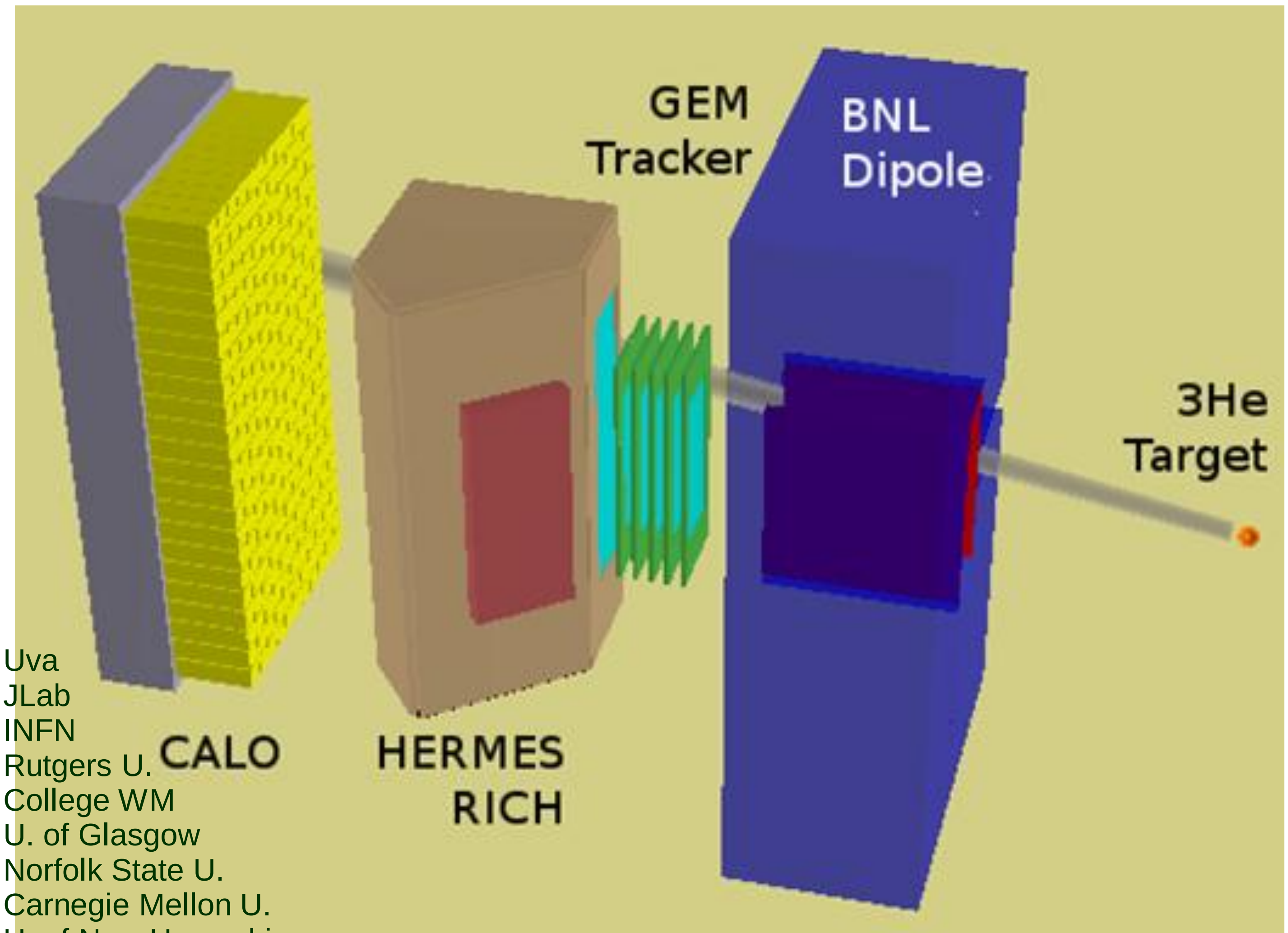
kaon Identification capability on SBS

SBS Spectrometer in Hall A

- High luminosity ~10^{39}/s/cm^2
- Moderate acceptance
- Forward angles
- Reconfigurable detectors

Rather standard set-up, state of the art tracking detector to sustain high background

High photons up to 250 MHz/cm^2 and electrons 160 kHz/cm^2 background (in Form-Factors experiments)



Uva
JLab
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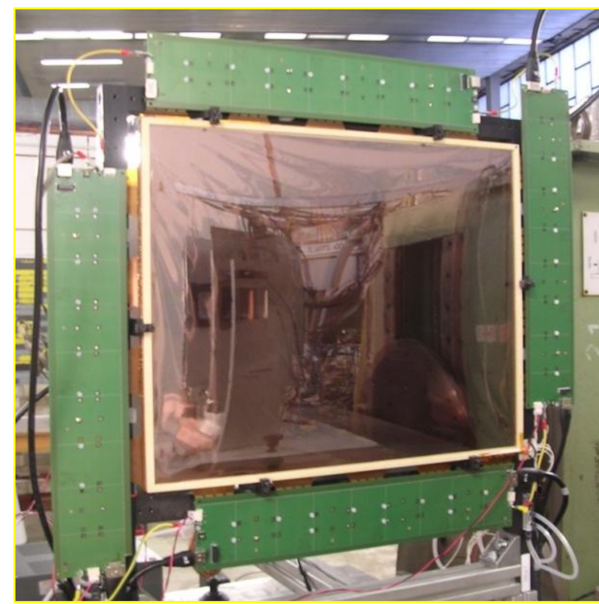
Rutgers U.
College WM
U. of Glasgow
Norfolk State U.
Carnegie Mellon U.
U. of New Hampshire

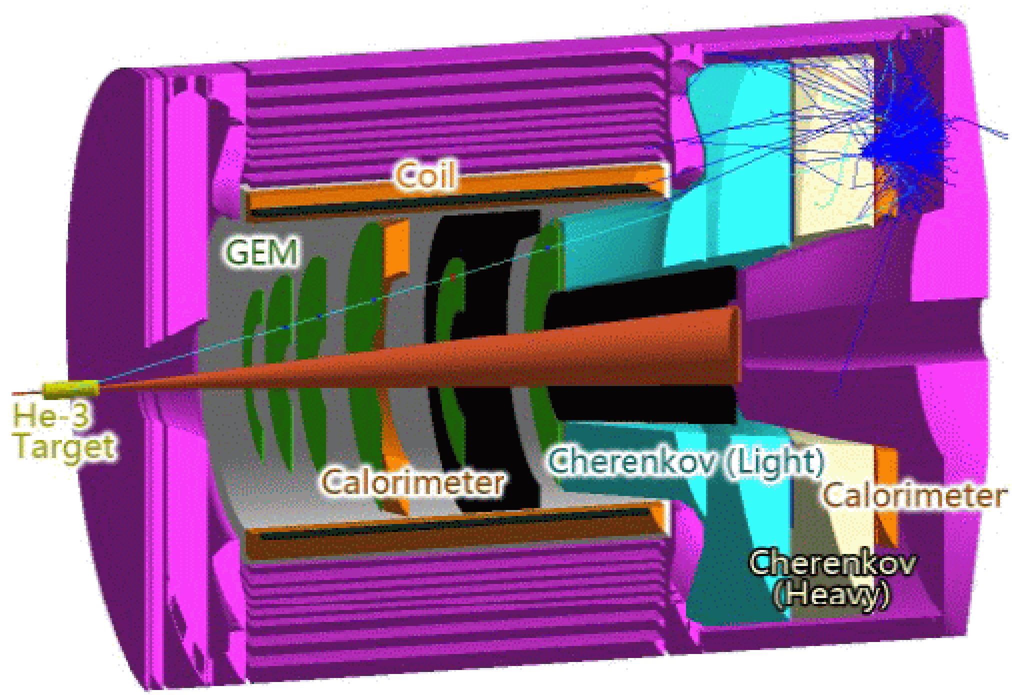


40x150 cm^2 GEM Tracker
70 μm spatial resolution

SoLID Configuration for SIDIS with ^{3}He and NH_3 Targets

- Beam energy = 11 GeV and 8.8 GeV
- Solenoid Magnet
- Luminosities:
  - ^{3}He (neutron) : 10^{36} N/cm^2/s
  - NH_3 (proton) : 10^{35} N/cm^2/s
- Full azimuthal angle coverage
  - Crucial for 4D mapping of asymmetries
  - Reduces systematics when extracting various moments
- Tracking with GEMs (6 GEM planes)
- Electron Identification:
  - EM calorimeter for large angle and high momentum
  - EM calorimeter and light gas Cerenkov for forward angle
- Pion identification:
  - Heavy Gas Cerenkov and TOF (Multi-Resistive Plate Chamber)
- Fast pipeline electronics for DAQ

Adapted from Kalyan Allada (DIS2012)



- Key device to achieve high-precision mapping and minimizing systematics
- Large acceptance: enable 4D-mapping
- Full/symmetric azimuthal angular coverage: small systematics
- Device shared by three SIDIS and a parity-violation DIS experiments

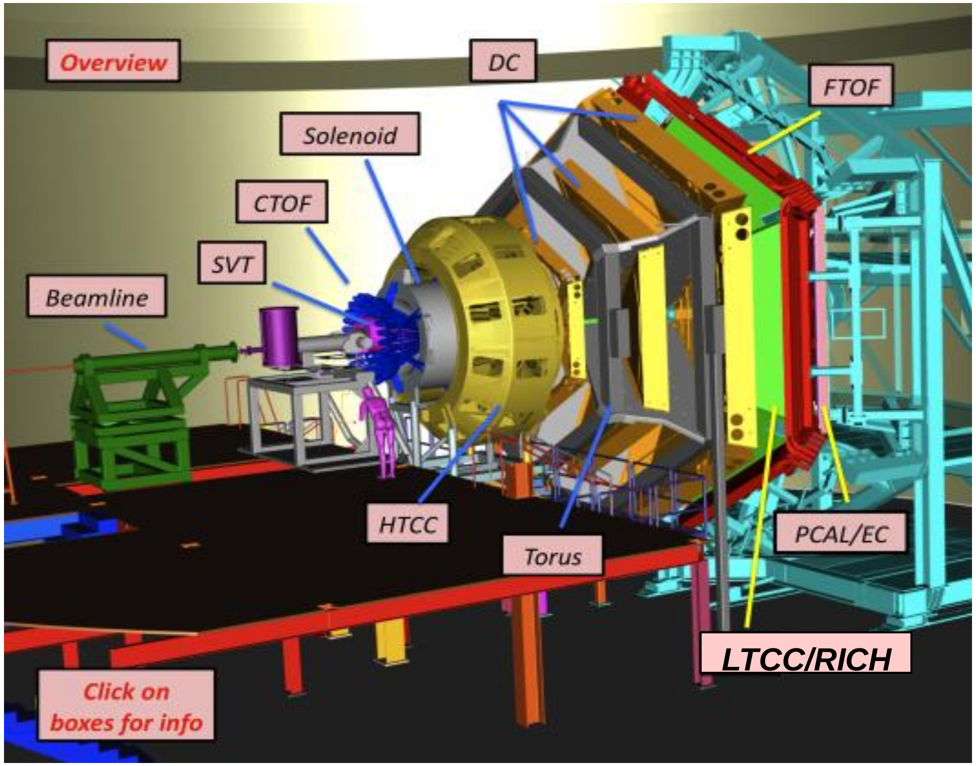
JLab HallB (Clas12)

New ~2π toroid detector (CLAS12) with extended hadron ID (RICH)

+ forward tagger for quasi real photons

+ new long/trans polarized H/D targets

→ High multiplicity event reconstruction

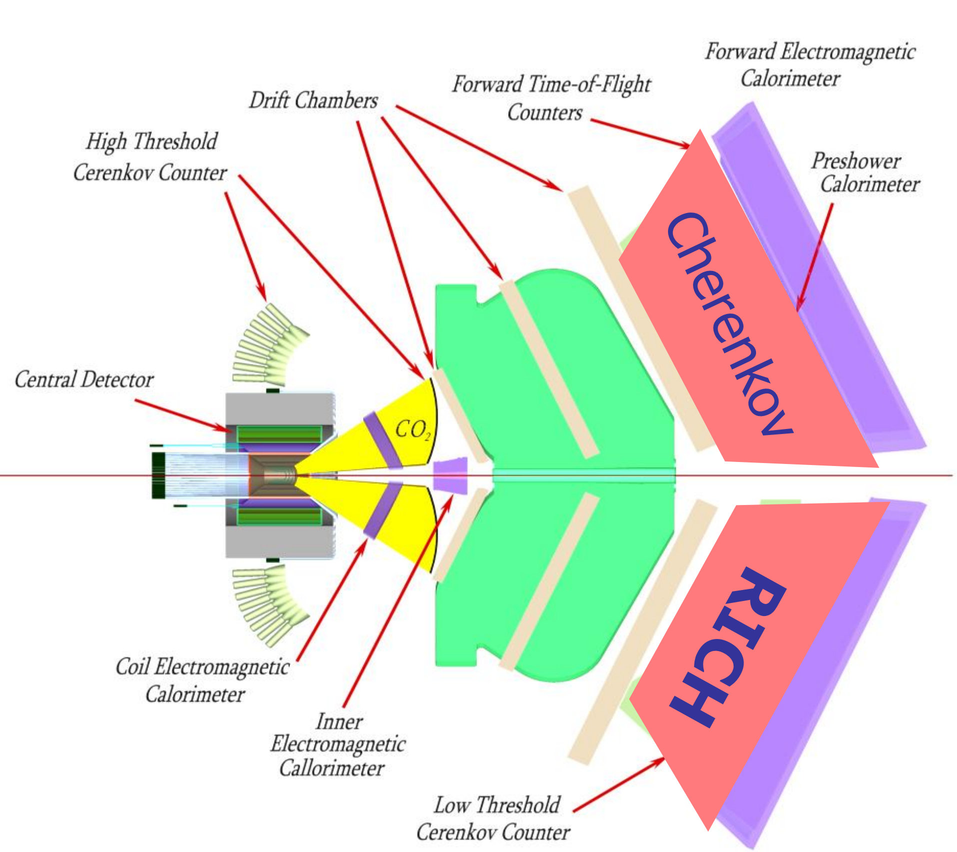


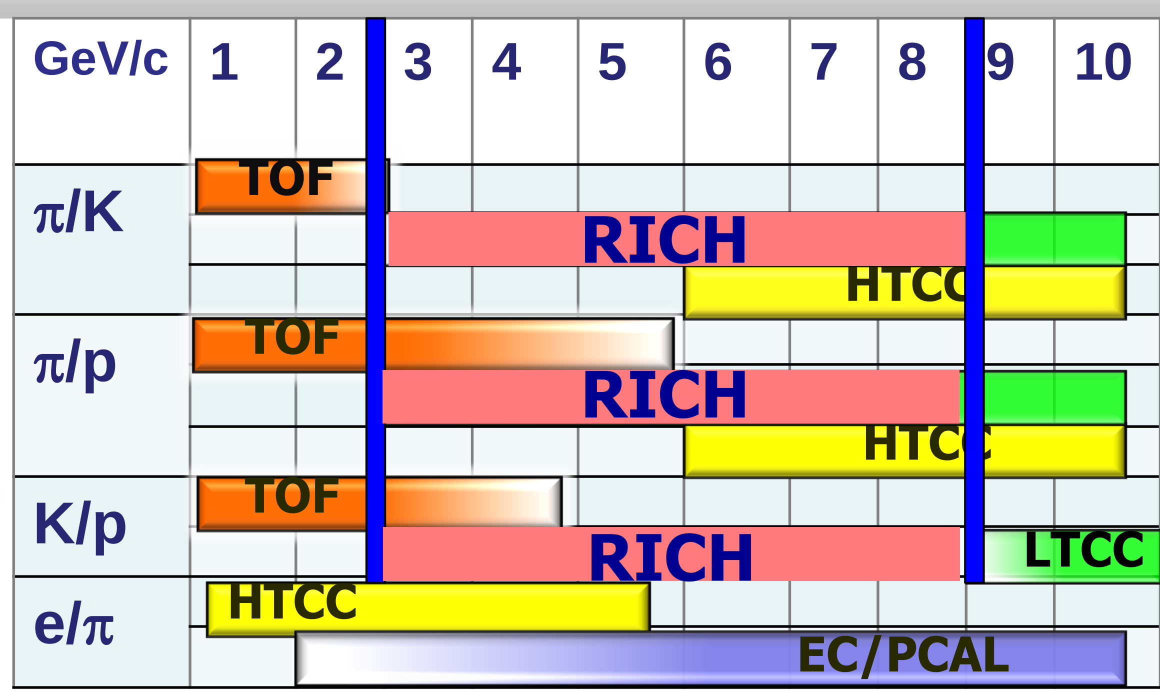
Several experiments proposed on TMD and SIDIS in general

Extended set of measurements in wide kinematical ranges in Q^2 and P_T

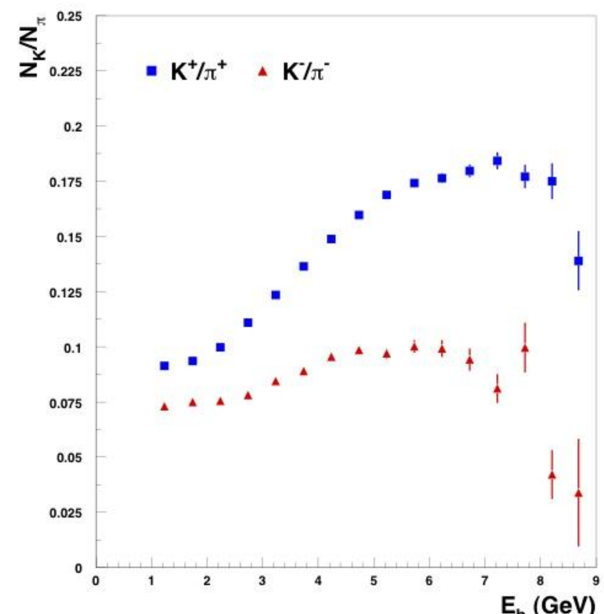
→ k_T dependent flavor decomposition, leading and sub-leading effects separation ...

CLAS12 PID





4-5 σ π/K separation **@ 8 GeV/c**



- **Aerogel** mandatory to separate hadrons in the 2-8 GeV/c momentum range → collection of **visible Cherenkov light** → use of **PMTs (or SiPMs)**
- Hybrid optics (focusing + proximity) to minimize expensive photon detectors
- Challenging project ⇨ will start with one sector (of six)

JLab Hall C

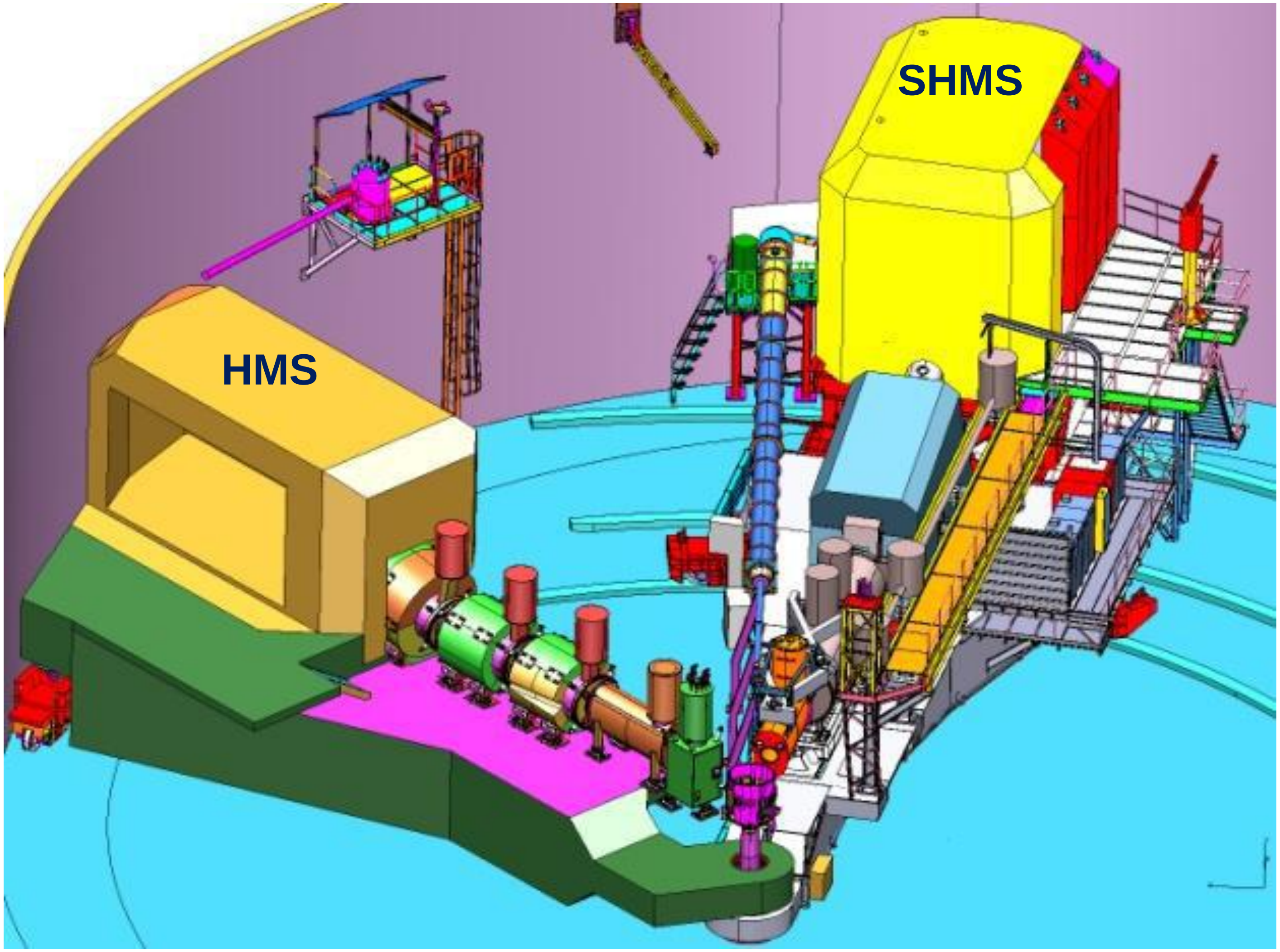
Existing HMS spectrometer and a new improved version (Super)HMS

Luminosity up to 10^{38}/s/cm^2

Small acceptance but precise event reconstruction

Systematics well under control

Precise measurements of production cross sections



The Multi-Hall SIDIS Program at 12 GeV

M. Aghasyan, K. Allada, H. Avakian, F. Benmokhtar, E. Cisbani, J-P. Chen, M. Contalbrigo, D. Dutta, R. Ent, D. Gaskell, H. Gao, K. Griffioen, K. Hafidi, J. Huang, X. Jiang, K. Joo, N. Kalantarians, Z-E. Meziani, M. Mirazita, H. Mkrtchyan, L.L. Pappalardo, A. Prokudin, A. Puckett, P. Rossi, X. Qian, Y. Qiang, B. Wojtsekhowski

JLab SIDIS working group

The complete mapping of the multi-dimensional SIDIS phase space will allow a comprehensive study of the TMDs and the transition to the perturbative regime.

Flavor separation will be possible by the use of different target nucleons and the detection of final state hadrons.

Measurements with pions and kaons in the final state will also provide important information on the hadronization mechanism in general and on the role of spin-orbit correlations in the fragmentation in particular.

Higher-twist effects will be present in both TMDs and fragmentation processes due to the still relatively low Q^2 range accessible at JLab, and can apart from contributing to leading-twist observables also lead to observable asymmetries vanishing at leading twist. These are worth studying in themselves and provide important information on quark-gluon correlations.

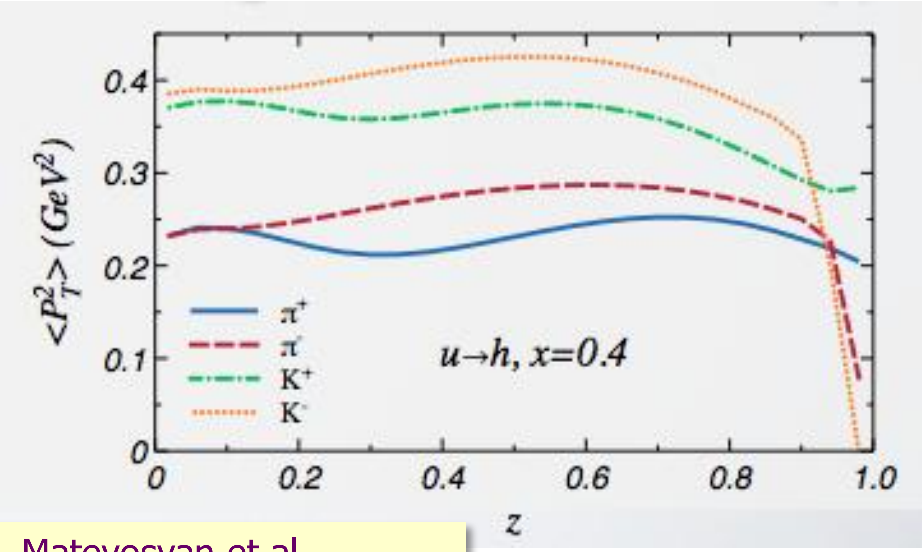
TMDs MultiHall exp. at JLab/12GeV

		Quark			Experiment								
		U	L	T	Test SIDIS		Complete TMDs investigation			Precise Measurements			
Nucleon	U	f_1		$h^{\perp}_1$ Boer-Mulders	$\pi^\pm$ $K^\pm$	π^0	$\pi^{\pm,0}$ $K^{\pm,0}$						
	L		G_1 Helicity	$h^{\perp}_{1L}$ Worm-gear				$\pi^{\pm,0}$ $K^{\pm,0}$			$\pi^\pm$		
	T	$f^{\perp}_{1T}$ Sivers	$g^{\perp}_{1T}$ Worm-gear	h_1, $h^{\perp}_{1T}$					$\pi^{\pm,0}$ $K^\pm$	$\pi^{\pm,(0)}$ $K^\pm$	$\pi^\pm$	$\pi^\pm$	
Target					LH2, LD2	LH2, LD2	LH_2 + LD_2	NH_3, ND_3 or ^6LiD or HD	HD	**^3He**	**^3He**	**NH_3**	
Detector					HMS SHMS	HMS SHMS + π^0 detector	CLAS12	CLAS12 + RICH	CLAS12 + RICH	SBS + HERMES RICH	SoLID	SoLID	
Lumi ($cm^{-2}s^{-1}$)					10^{36}	10^{36}	10^{35}	10^{35}	10^{34}	**$4\ 10^{36}$**	**$2\ 10^{36}$**	**10^{35}**	
Experiment ID					E12-06-104 E12-09-017	C12-12-102	E12-06-112, E12-09-008	E12-07-107, E12-09-009	C12-11-111	E12-09-018 (SIDIS)	E12-10-006 E12-11-007 (SoLID n)	C12-11-108 (SoLID p)	

Precision test of SIDIS

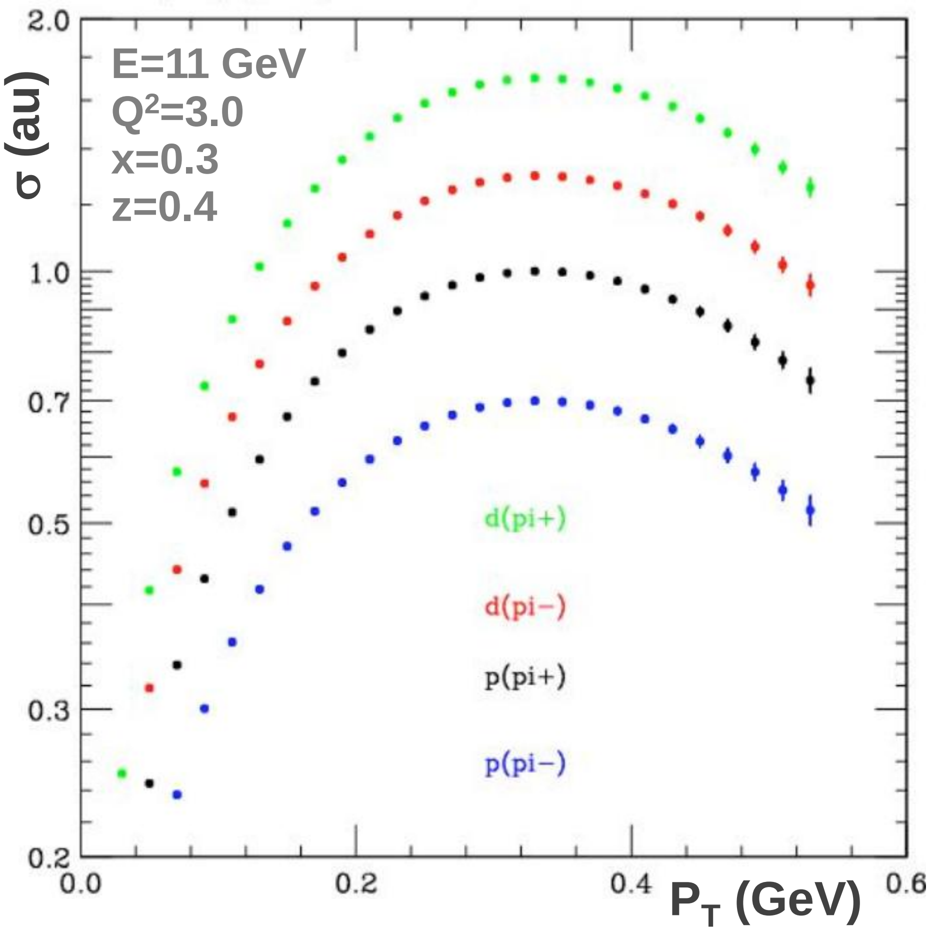
Experiment	Title	Main Purpose	Tecnique
E12-06-104 P. Bosted, R.Ent, H. Mkrtchyan et al.	Measurement of the Ratio $R = \sigma_L/\sigma_T$ in Semi-Inclusive DIS	Check $R \sim 1/Q^2$ at fixed x	Measure R dependence on Q^2, P_T and z on H and D
C12-12-102 R.Ent, T. Horn, H. Mkrtchyan et al.	Measurement of the Ratio $R = \sigma_L/\sigma_T$ in Exclusive and Semi-Inclusive p^0 Production	SIDIS behavior at JLab energies σ_L/σ_T on π^0 info on twist-4 (σ_L=0 at 1/Q) Combined to E12-06-104 verify $\pi^0=(\pi^++\pi^-)/2$ Test z->1 exclusive regime	R dependence on Q^2, t and x on H and D
E12-09-017 P. Bosted, R.Ent, H. Mkrtchyan et al.	Transverse Momentum Dependence of Semi-Inclusive Pion and Kaon Production	Constraint up and down quarks transverse momentum (combined to CLAS12 E12-06-112)	Map π and K charged cross section in SIDIS over x, Q^2, z and P_T<0.5 GeV Full ϕ coverage

Transverse Motion of quarks



H. Matevosyan et al.
Phys.Rev.D85:014021,2012

Expected precision from E12-09-017



Cover wide range in Q^2

Full coverage of ϕ

Larger p_T and z range

Charged pions and kaons production

$P_T = p_T + z\,k_T + O(k_T^2/Q^2)$

Toward flavor and helicity dependence of

the transverse motion of quark (and gluon)

Comprehensive TMDs measurements

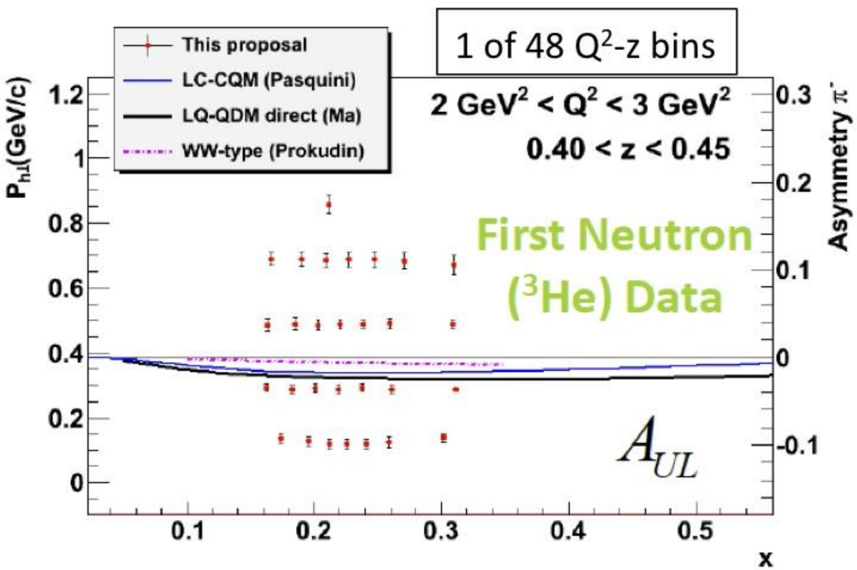
Experiment	Title	Main Purpose	Tecnique
E12-06-112 H. Avakian, K. Joo, Z.E. Meziani, B. Seitz et al.	Probing the Proton's Quark Dynamics in Semi-Inclusive Pion Production at 11 GeV	Extract $\cos\phi$ and $\cos2\phi$ moments (Boer-Mulders TMD and Cahn effect at 1/Q)	Azimuthal asymmetries of π on unpol. H and D targets and longitudinally polarized beam as Q^2 and p_T dependence
E12-09-008 H. Avakian, M. Contalbrigo, K. Joo, Z.E. Meziani, B. Seitz et al.	Studies of the Boer-Mulder Asymmetri in Kaon Electroproduction with Hydrogen and Deuterium Targets	Extend previous exp. to kaon	
E12-07-107 H. Avakian, P. Bosted, K. Griffioen, K. Hafidi, P. Rossi et al.	Studies of Spin-Orbit Correlations with Longitudinally Polarized Target	Extract $\sin2\phi$ moment (Worm-gear TMD), study $\sin\phi$ (higher twist); transverse momentu dependat of quark helicity	SSA and DSA of π on H and D longitudinally polarized targets with long. Pol. Beam.; x, z, P_T and Q^2 moments dependence
E12-09-009 H. Avakian, E. Cisbani, K. Griffioen, K. Hafidi, P. Rossi et al.	Studies of Spin-Orbit Correlations in Kaon Electroproduction in DIS with Polarized Hydrogen and Deuterium Targets	Extend previous exp. to kaon	
C12-11-111 H. Avakian, F. Klein, M. Aghasyan, K. Joo, M. Contalbrigo et al.	Transverse spin effects in SIDIS at 11 GeV with a transversely polarized target using CLAS12 Detector	Extract moments of Transversity, Sivers and Pretzelosity TMDs and Worm-gear; flavor decomposition	TTSA and of π and K on HD transversely pol. target at x Q^2, z and P_T; measure DSA

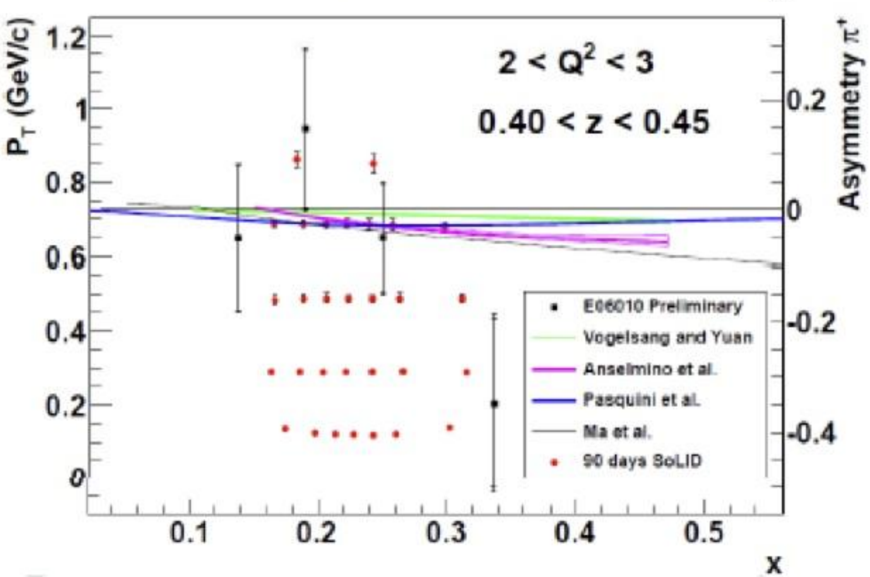
Precise TMDs measurements

Experiment	Title	Main Purpose	Tecnique
E12-09-018 *G. Cates, E. Cisbani, G. B. Franklin, A. Puckett, B. Wojtsekhowski et al.*	Target Single-Spin Asymmetries in Semi-Inclusive Pion and Kaon Electroproduction on a Transversely Polarized ^{3}He Target using Super BigBite and BigBite in Hall A	Extract Sivers, Collins and Pretzelosity neutron asymmetries on π and K with high statistics Explore for the first time the high x valence region (with overlap to HERMES, COMPASS, Jlab 6GeV data at lower x)	3D binning on the relevant variables: x, $P_\perp$ and z, for both hadrons; 2 Q^2 values
E12-10-006 *H. Gao, X. Qian, J.-P. Chen, J.-C. Peng et al.*	Target Single Spin Asymmetry in Semi-Inclusive Deep-Inelastic (e, e′$\pi^\pm$) Reaction on a Transversely Polarized ^{3}He Target at 8.8 and 11 GeV	Extract Sivers, Collins and Pretzelosity neutron asymmetries on π with very high statistics and minimize systematics; multi term fitting	4D binning on the relevant variables: x, $P_\perp$ and z and Q^2
C12-11-008 *H. Gao, K. Allada, J.-P. Chen, Z.-E. Meziani et al.*	Target Single Spin Asymmetry in Semi-Inclusive Deep-Inelastic (e, e′$\pi^\pm$) Reaction on a Transversely Polarized Proton Target	Extend previuos experiment to proton target	
E12-11-007 *J.P. Chen, J, Huang, Y. Qiang, W.B. Yan et al.*	Asymmetries in Semi-Inclusive Deep-Inelastic (e, e'$\pi^\pm$) Reactions on a Longitudinally Polarized ^{3}He Target at 8.8 and 11 GeV	Precise study of Worm-gear TMDs (combined to E12-10-006)	Multidimensional mapping as in E12-10-006

Sivers Moments Expected Stats.

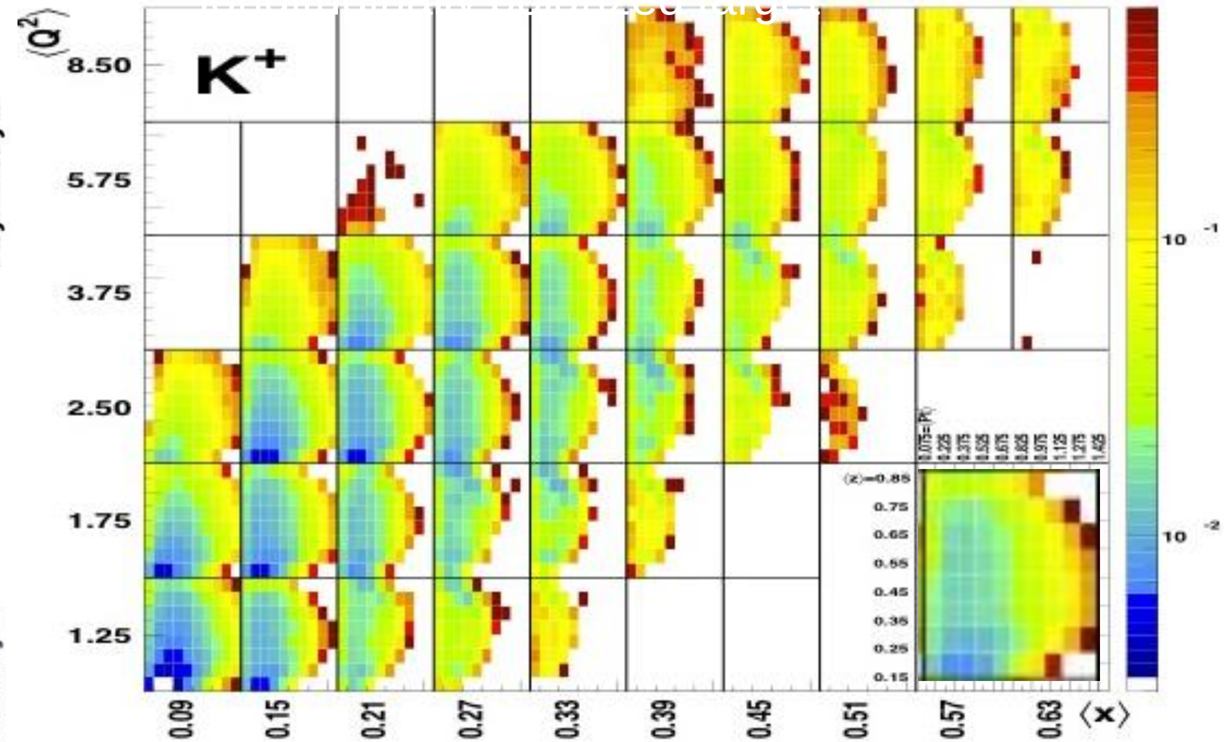
SOLID: $e\,^3He \rightarrow e'\pi^{+/-}X$



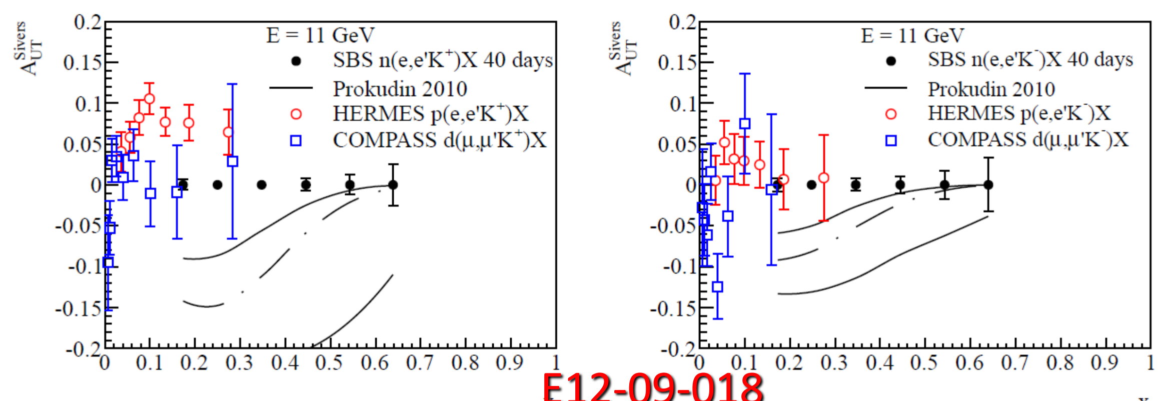


E12-11-007

CLAS12: $e\,p \rightarrow e'K^{+/-}X$ **C12-11-111**

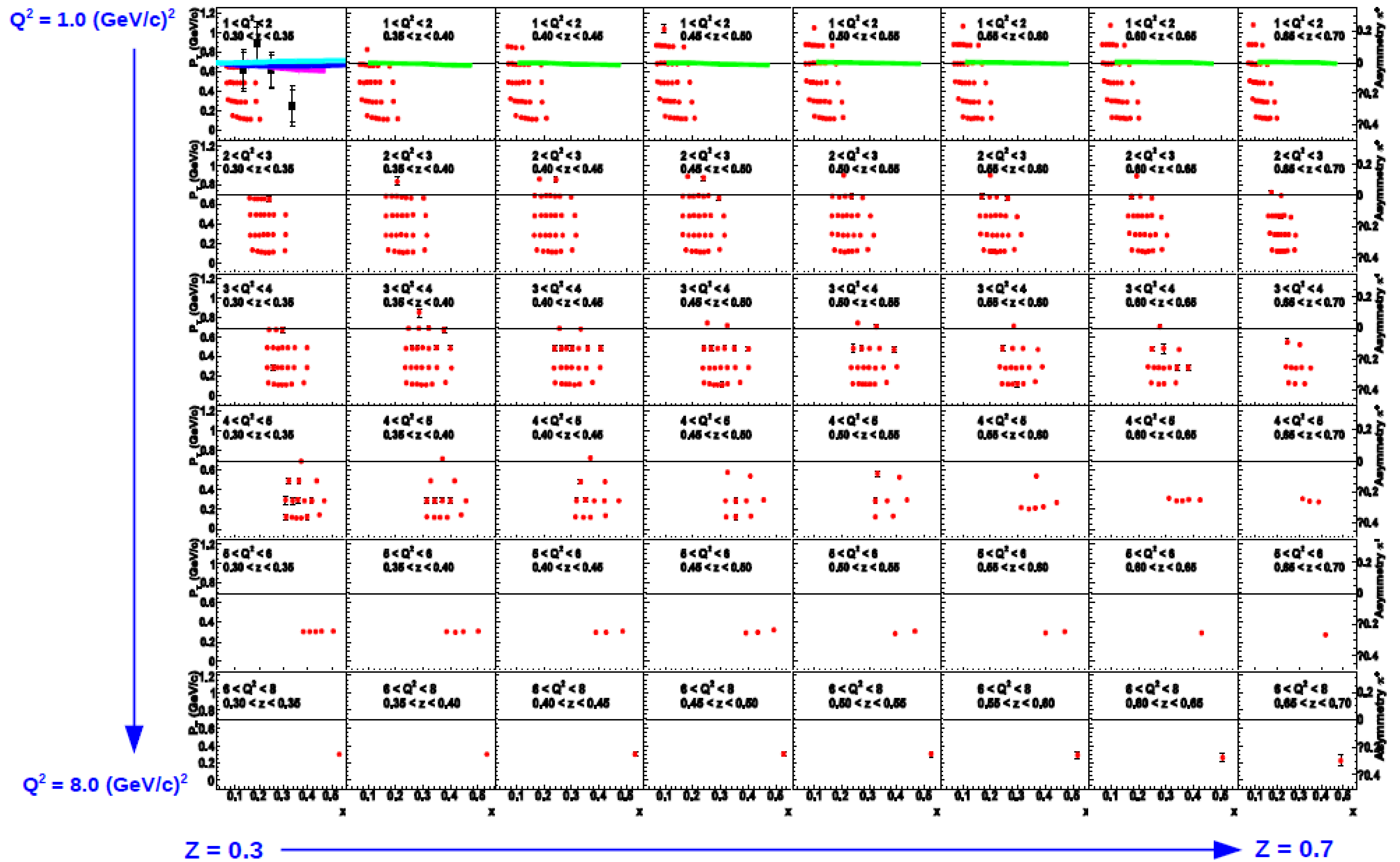


SBS: $e\,^3He \rightarrow e'K^{+/-}$ X(transverse target)



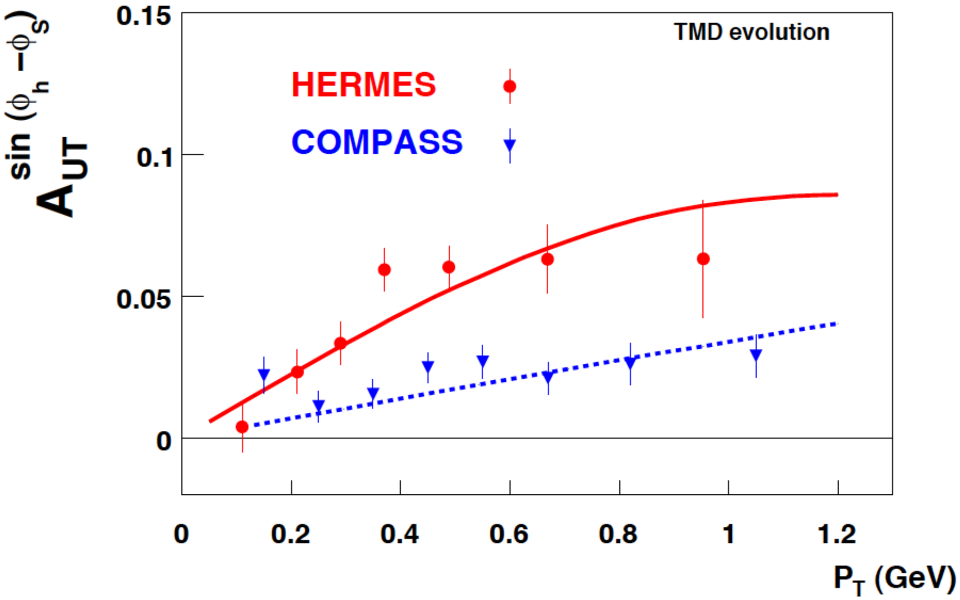
E12-09-018

SoLID Sivers/Transversity: precise 4D mapping

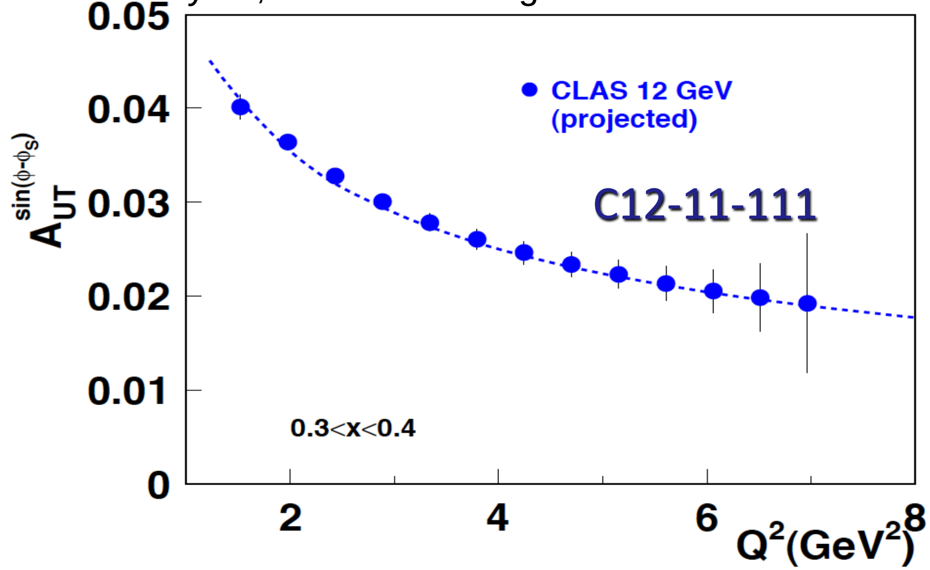


TMD Studies Expected Effects

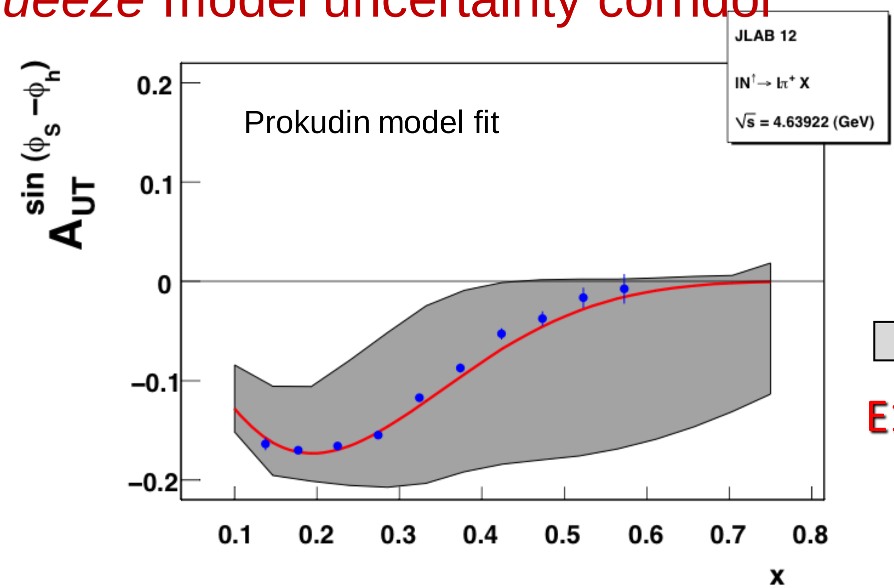
The extended Q2 coverage + HERMES and COMPASS data will constrain the Sivers evolution



Aybat, Prokudin & Rogers : arXiv:1112.4423



Squeeze model uncertainty corridor



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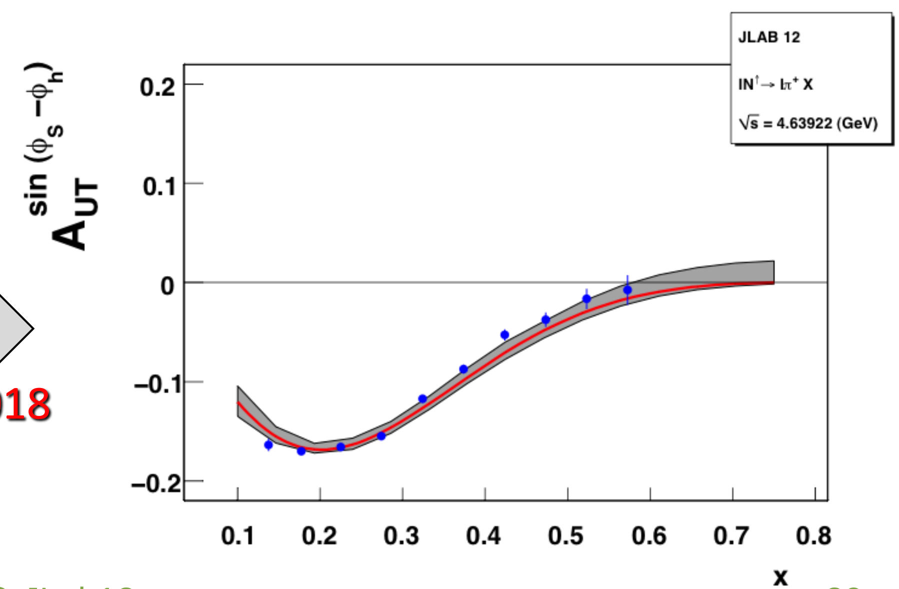
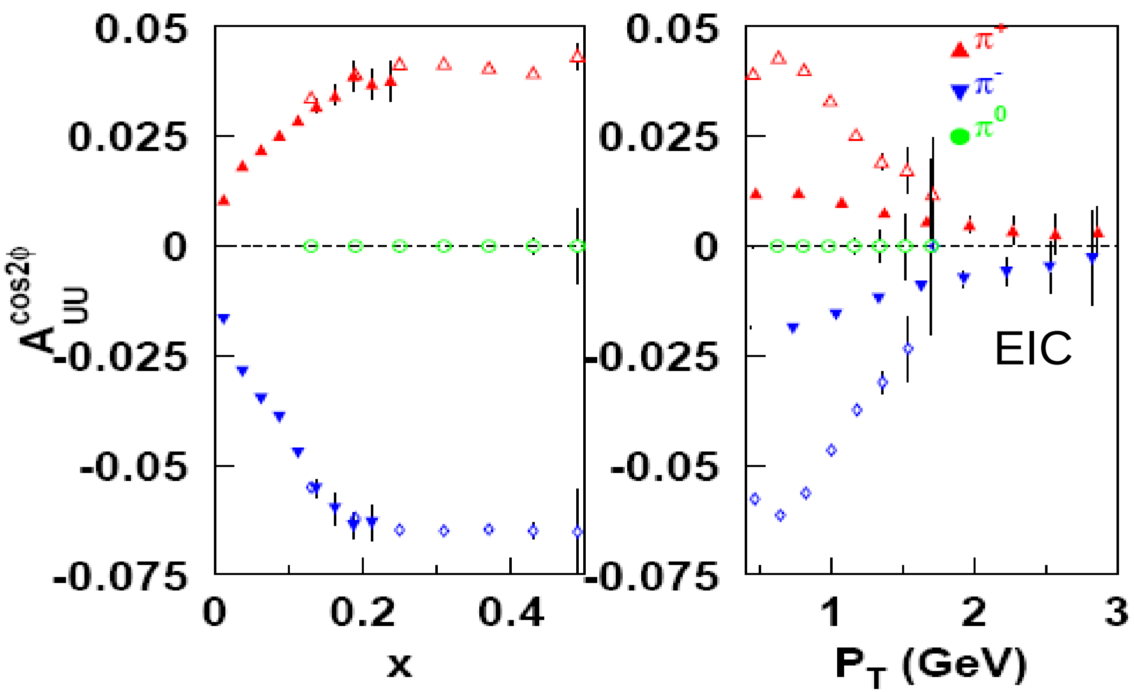
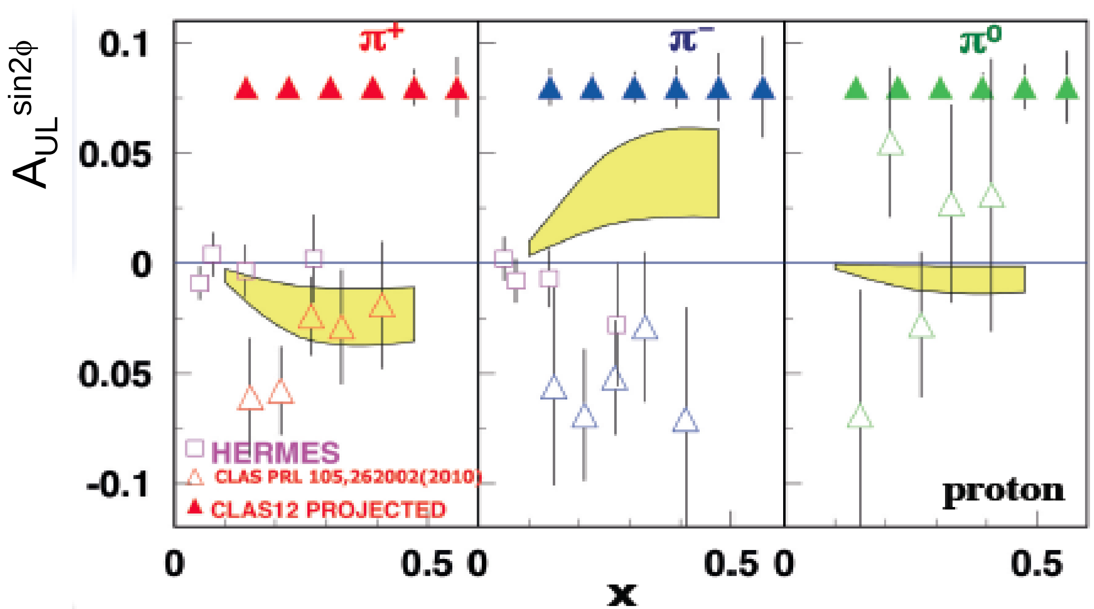


Poorly known or unknown TMDs

Boer-Mulders (E12-06-112)

Test transition from non-perturbative description (low P_T) to perturbative (high P_T)



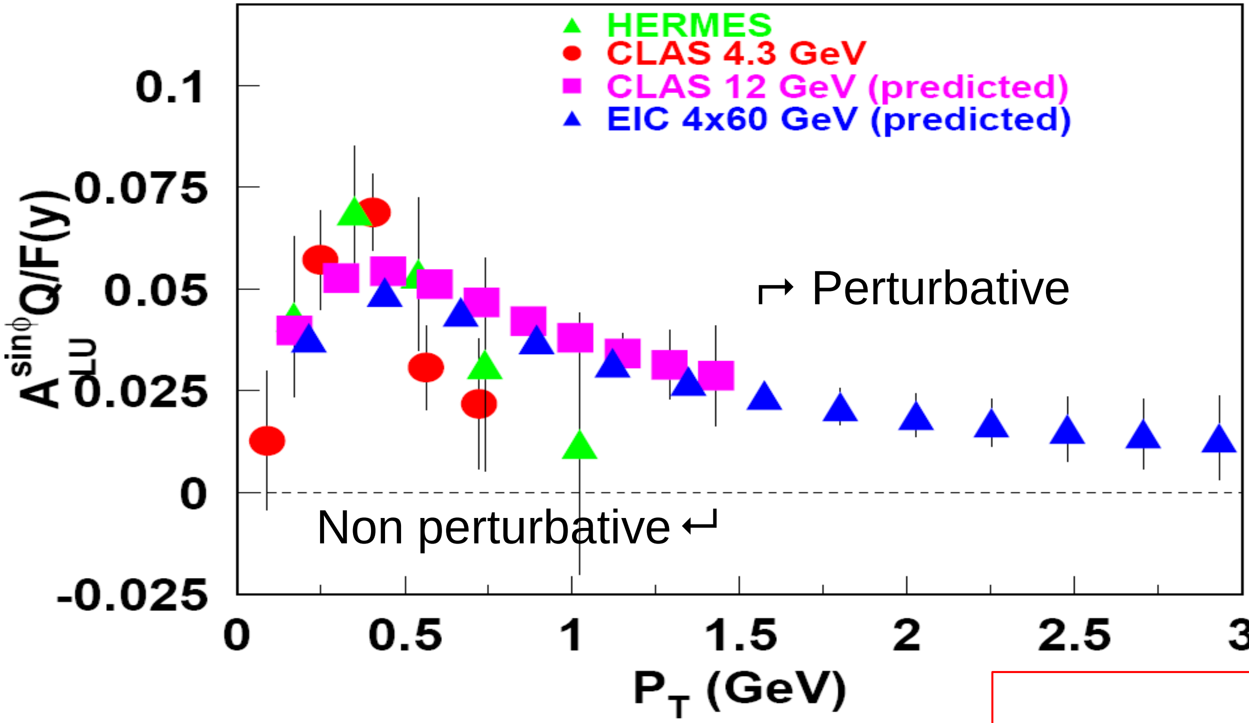


Worm-gear (E12-07-107)

First «precise» measurements may confirm the negligible signal

Precise measurement of A_1 (helicity) ...

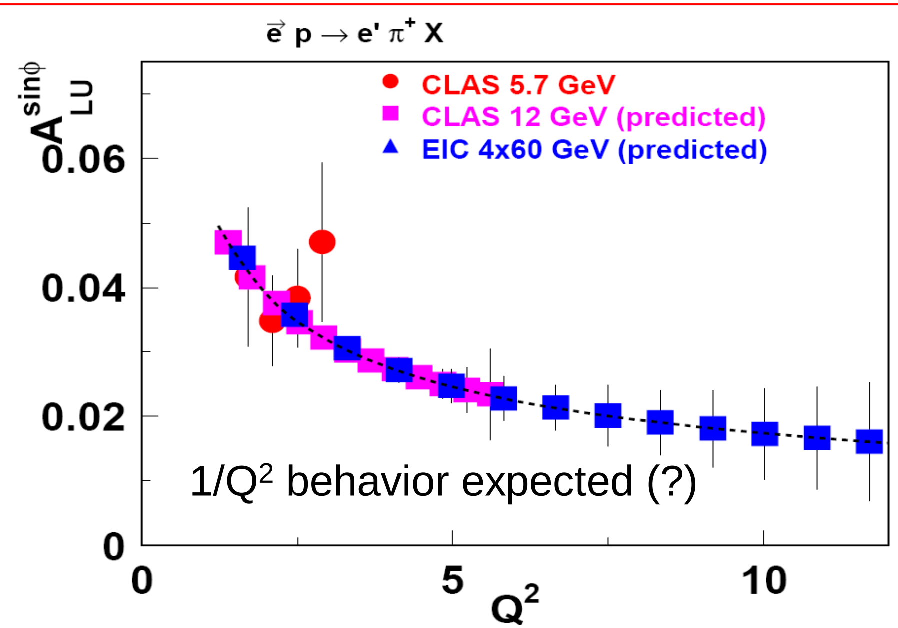
P_T and Q^2-dep Higher Twist $A_{LU}^{\sin\phi}$



Study for SSA transition from non-perturbative to perturbative regime.

E12-06-112

Study for Q^2 dependence of beam SSA allows to check the higher twist nature and access quark-gluon correlations



Some issues

- High statistics measurements needs small systematics
  - from detectors (new equipments require time for adequate undestanding!)
  - from models (competing processes, radiative corrections, two photons, nuclear effects ...)

- Nucleon structure investigation is high priority of JLab, however
  - Other hot scientific topics (parity violating experiments, search of hidden matter and energy ...), are gaining more and more importance
  - beam time is limited

From ^{3}He to n (nuclear effects)

Proven to work in DIS extraction (C. Ciofi degli Atti et al. 1993)

$$\left\{\begin{aligned} g_1^{^3He} &= P_n g_1^n + 2P_p g_1^p \\ P_n &= 0.86^{+0.036}_{-0.02} \\ P_p &= -0.028^{+0.009}_{-0.004} \end{aligned}\right.$$

assume ⇨

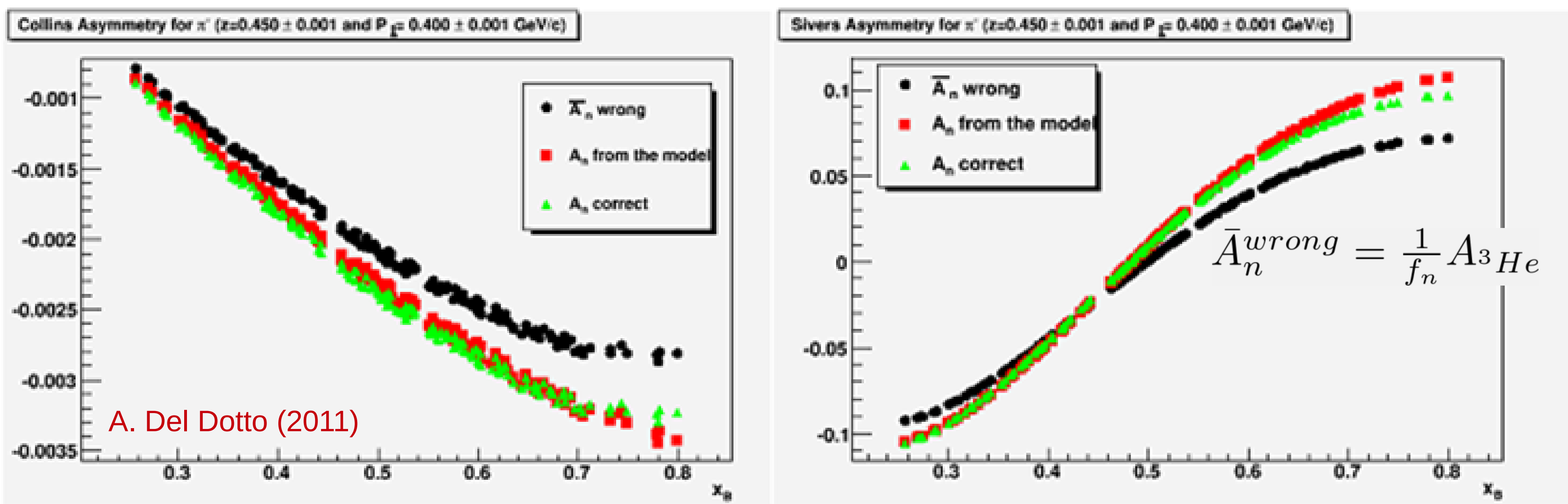
$$A_{^3He} = P_n f_n \boxed{A_n} + P_p f_p A_p$$

$$f_n = 1 - f_p$$

$$f_p = 2\sigma_p/\sigma_{^3He} \sim 0.2 \text{ from data}$$

Scopetta approach (2007): Bjorken limit, Impulse Approximation

Assume asymmetries → apply ^{3}He realistic spectral function → extract them back.



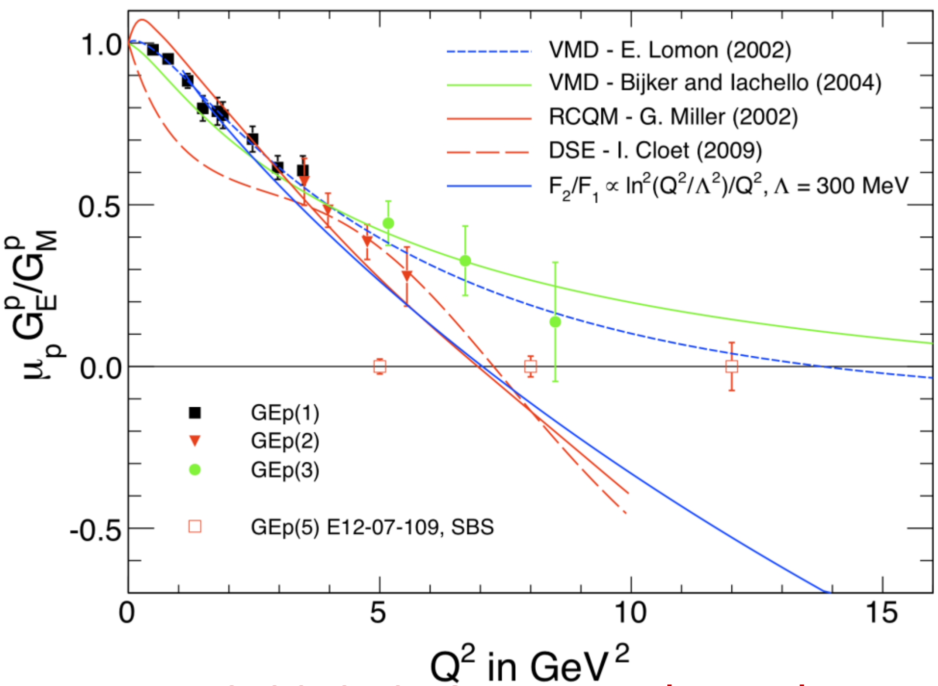
Improvement in progress (Del Dotto, Salmè, Scopetta):

- Light front ^{3}He spectral function (consistent fully Poincarè covariant formalism)
- Release Bjorken limit

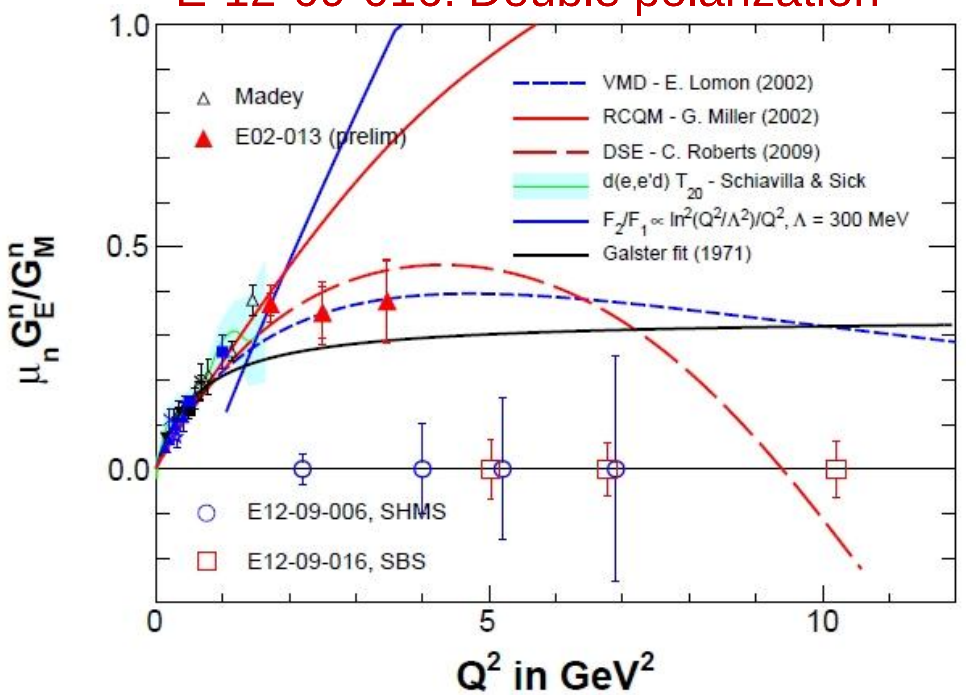
Scopetta Talk

Electromagnetic Nucleon Form Factors @12GeV

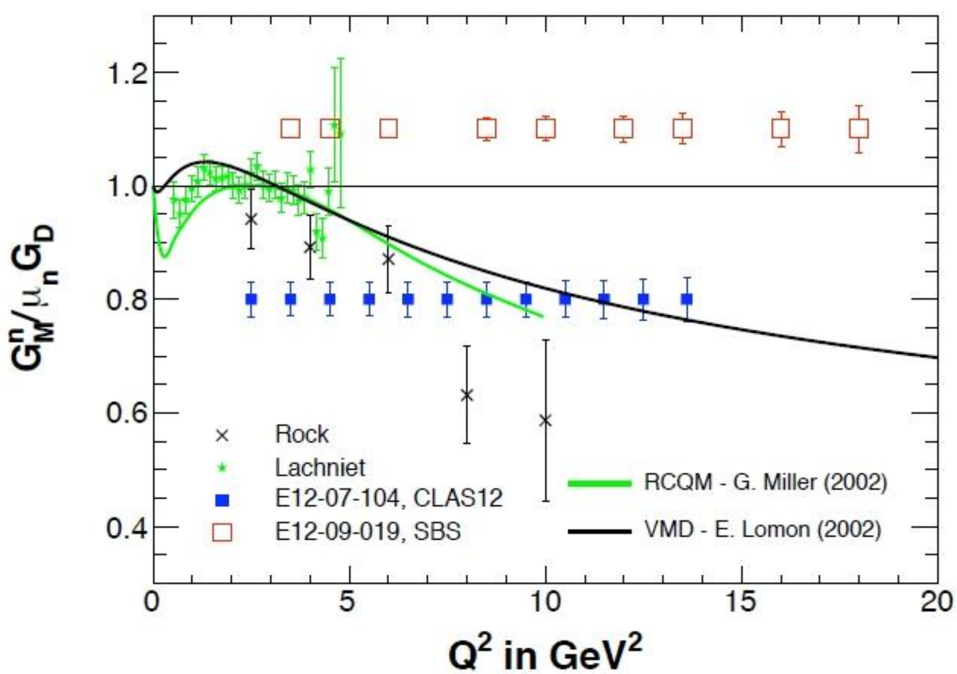
E-12-07-109: Polarization transfer



E-12-09-016: Double polarization



E-12-09-019: Cross section ratio



Extended measurements of p/n form factors at high Q^2

- **Test different models (including different contributions from the quark OAM)**
- **Investigate the transition region (perturbative / non perturbative)**
- **Constraint the H and E GPDs**

Conclusions

JLab energy upgrade will offer new exciting opportunities to study the spin/momentum structure of the nucleons:

- high precision
- unexplored phase space, large kinematical coverage
- flavor decomposition (p,n)⇨(π,K)
- all (leading twist) TMDs will be measured

Large technological efforts is in progress to optimally exploit these opportunities

Expected results will likely provide rich set of new informations

Analysis of the data will require precise knowledge of the new detectors and physics assumptions

First beam in HallA beginning of 2014, first «physics» beam to all Halls expected beginning of 2015